SIMULATION RESULTS OF THE HUYGENS PROBE ENTRY AND DESCENT TRAJECTORY RECONSTRUCTION ALGORITHM

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ABSTRACT

Cassini/Huygens is a joint NASA/ESA mission to explore the Saturnian system. The ESA Huygens probe is scheduled to be released from the Cassini spacecraft on December 25, 2004, enter the atmosphere of Titan in January, 2005, and descend to Titan's surface using a sequence of different parachutes. To correctly interpret and correlate results from the probe science experiments and to provide a reference set of data for "ground-truthing" Orbiter remote sensing measurements, it is essential that the probe entry and descent trajectory reconstruction be performed as early as possible in the post-flight data analysis phase. The Huygens Descent Trajectory Working Group (DTWG), a subgroup of the Huygens Science Working Team (HSWT), is responsible for developing a methodology and performing the entry and descent trajectory reconstruction.

This paper provides an outline of the trajectory reconstruction methodology, preliminary probe trajectory retrieval test results using a simulated synthetic Huygens dataset developed by the Huygens Project Scientist Team at ESA/ESTEC, and a discussion of strategies for recovery from possible instrument failure.

Key words: Huygens mission, trajectory reconstruction.

1. INTRODUCTION

1.1. Probe Mission Overview

The Huygens Probe is the ESA-provided element of the joint NASA/ESA/ASI Cassini/Huygens mission to Saturn and Titan (Lebreton and Matson, 2002). Cassini/Huygens was launched on October 15, 1997 and arrived at Saturn on July 1, 2004. Following two orbits of Saturn, the Huygens Probe will be released on December 25, 2004 and will reach Titan on January 14, 2005.

The Huygens probe carries six instruments that will perform scientific measurements of the physical and chemical properties of Titan's atmosphere, measure winds and global temperatures, and investigate energy sources important for the planet's chemistry throughout the descent mission. These instruments are the

- **Aerosol Collector and Pyrolyser (ACP)**: investigation of atmospheric aerosols in cooperation with the GCMS instrument (Israel *et al.*, 2002);
- **Huygens Atmospheric Structure Instrument (HASI)**: spacecraft acceleration measurements during the entry phase, measurement of atmospheric properties (i.e, pressure, temperature, and electric properties) during the descent phase (Fulchignoni *et al.*, 2002)
- **Descent Imager/Spectral Radiometer (DISR)**: optical/IR images and measurement of Solar Zenith Angle (SZA) (Tomasko *et al.*, 2002);
- **Doppler Wind Experiment (DWE)**: measurement of zonal wind speeds during the descent phase (Bird *et al.*, 2002);
- **Gas Chromatograph and Mass Spectrometer (GCMS)**: measurement of atmospheric composition and mole fraction of major atmospheric constituents (Niemann *et al.*, 2002);
- **Surface Science Package (SSP)**: Speed of sound, altitude, and surface properties during the descent phase (Zarnecki *et al.*, 2002);

All instruments will deliver important data containing information about the probe trajectory (and attitude). Huygens will transmit its data to the Cassini Orbiter, targeted to flyby Titan at a periapse distance of 60,000 km, during the mission. The probe data will be recorded by the orbiter's solid state recorders for later transmission to Earth.

1.2. The Probe Entry and Descent Sequence

The Huygens probe entry and descent sequence is schematically shown in Fig. 1. The probe is protected

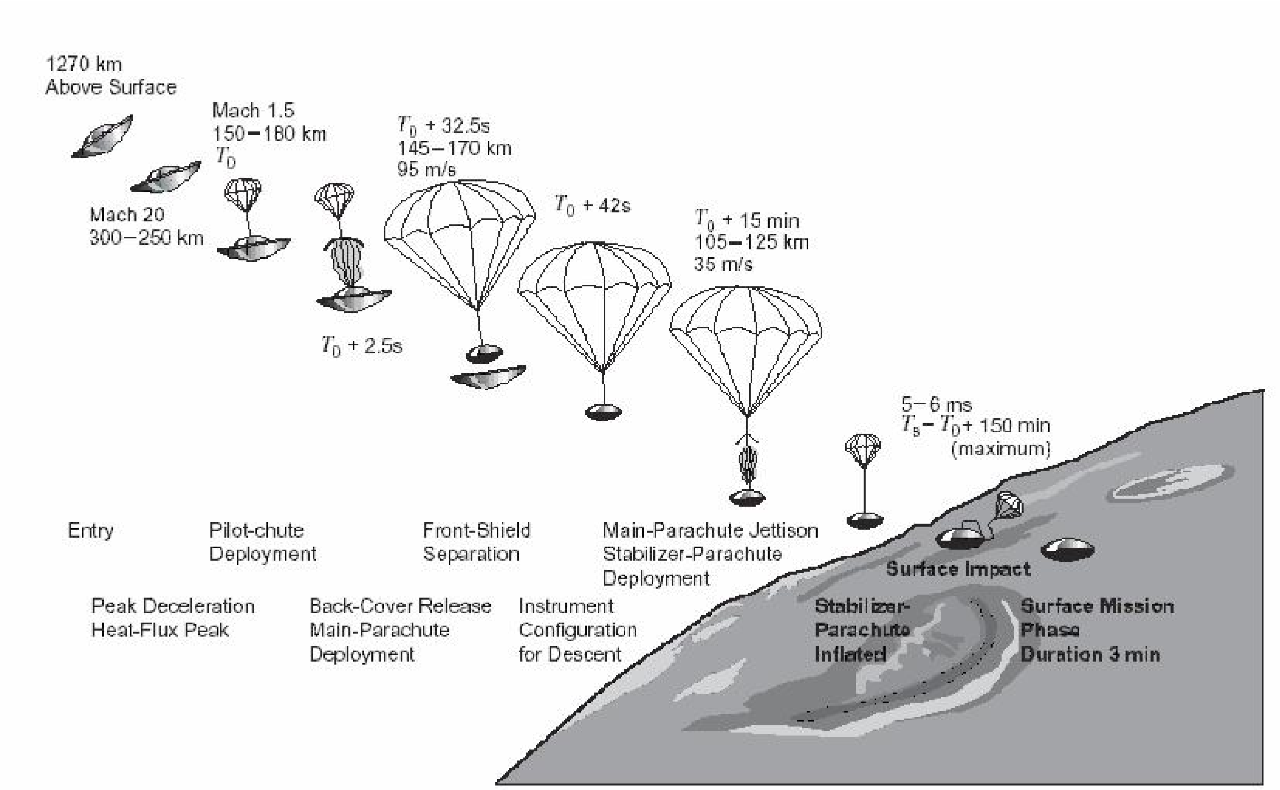

Figure 1. The Huygens probe entry and descent mission sequence;

from the atmospheric induced radiative and convective heat fluxes during entry by a 2.75 meter diameter front heat-shield as it decelerates from about Mach 22.5 to Mach 1.5 in just under five minutes. Approximately 4.45 minutes after entry the probe speed will have decreased to Mach 1.5 and the probe Central Acceleration Sensor Unit (CASU) will measure the deceleration threshold at a time designated as S_0. At S_0 the entry portion of the mission is complete and the descent mission commences.

Approximately 6.375 seconds after S_0 a parachute deployment device is fired through a breakout patch in the aft cover and a 2.59 m disk gap band (DGB) type pilot parachute is deployed. Two and one half seconds later, the probe aft cover is released and the 8.3 meter main DGB parachute is deployed. Nominally this event occurs at Mach 1.5 and an altitude of 160 km. After a 30 second delay (built into the sequence to ensure that the shield is sufficiently far below the probe to avoid possible instrument contamination), the probe speed has dropped to Mach 0.6 and the inlet ports of the probe Gas Chromatograph/Mass Spectrometer and Aerosol Collector and Pyrolyser instruments are opened and the booms of the Huygens Atmospheric Structure Instrument deployed.

The probe will descend beneath the main parachute for 15 minutes, at which time the main parachute is released and a 3.03 meter drogue parachute is deployed to carry the probe to Titan's surface. Throughout the approximately 2.5 hour parachute descent to the surface, Huygens will measure the chemical, meteorological, and dynamical properties of the Titan atmosphere. Probe experiment and housekeeping/engineering data will be transmitted to the orbiter at 8 kbit/s.

2. THE HUYGENS SYNTHETIC DATASET (HSDS)

The reconstruction of the Huygens probe will be done by the Huygens Descent Trajectory Working Group (DTWG) which is a subgroup of the Huygens Science Working Team (HSWT). To perform this task the DTWG has developed a dedicated tool, the DTWG tool, which will be described in more detail in Sec. 3.

In order to test the DTWG tool a simulated synthetic mission dataset (HSDS) was developed by the Project Scienctist Team (PST) at ESA/ESTEC (Pérez-Ayúcar *et al.*, 2004) and was validated by the various probe instrument teams. The file format and content is fully consistent with the interface conventions between the DTWG and the instrument teams and therefore provides a perfect test case for the reconstruction capabilities of the DTWG tool.

The production and validation of the HSDS comprises the following four steps:

1. The definition of an atmosphere profile and a mission scenario (i.e., definition of initial conditions, and various simulation parameters);
2. The simulation of the Huygens probe entry and descent trajectory using the official Huygens 3DOF trajectory simulation software DTAT (Castillo and Sánchez-Nogales, 2004);

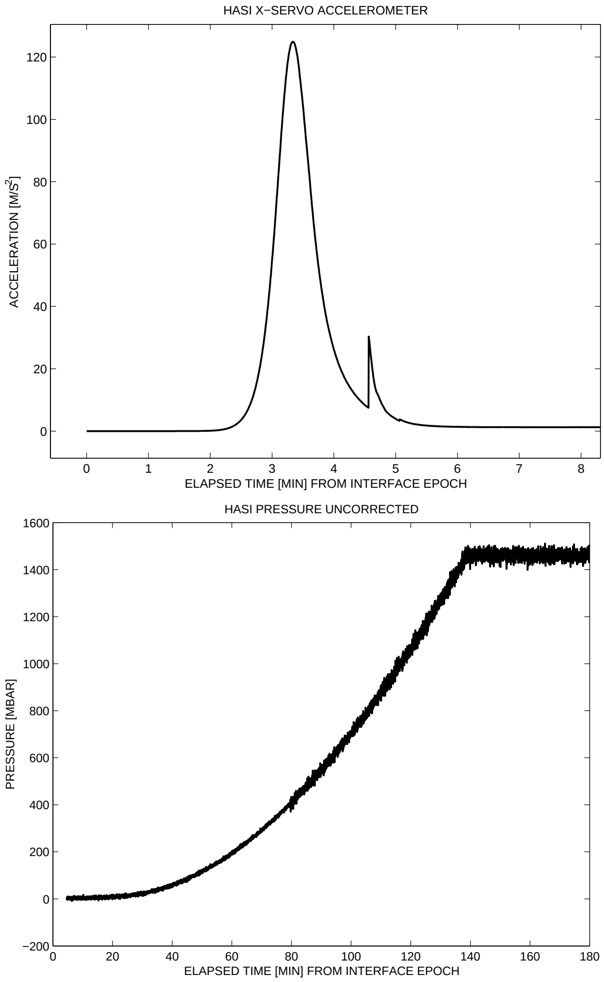

Figure 2. Examples for simulated sensor outputs of the HSDS; Upper panel: HASI X-Servo acceleration, Lower panel: HASI pressure profile;

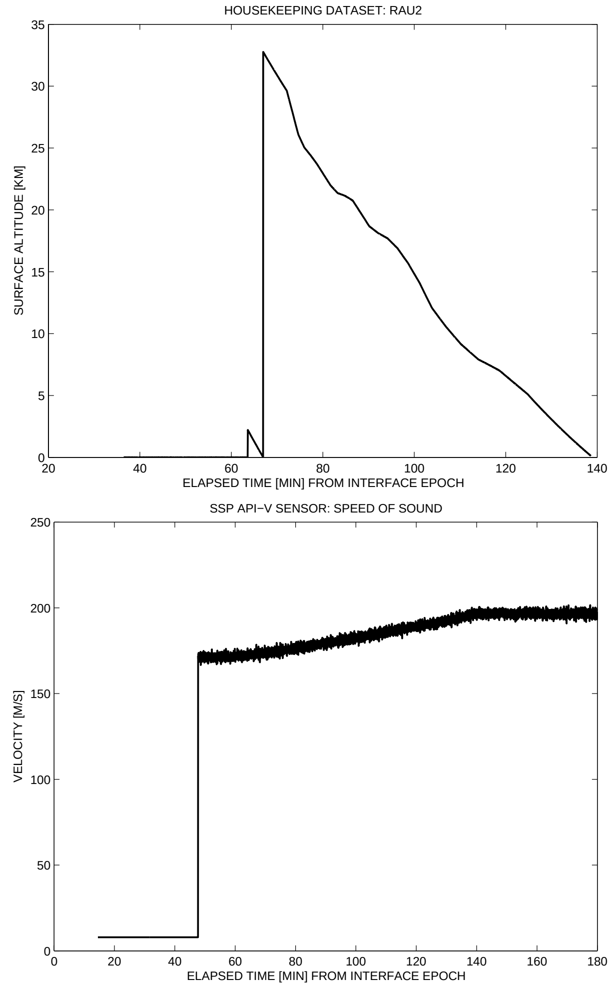

Figure 3. Examples for simulated sensor outputs of the HSDS; Upper panel: RAU altitude profile, Lower panel: SSP speed of sound measurements;

3. The simulation of sensor outputs on the basis of the simulated trajectory;

4. The validation of the sensor outputs by the various instrument teams (PIs);

There have to date been four deliveries of the HSDS from the PST, with a continuous refinement and implementation of new features in order to better simulate the expected instrument sensor output during the actual mission in January 2005. The latest version of the HSDS (ver. 1.4) comprises the following sensor models

- HASI (3-axis) accelerometer measurements during the entry phase, pressure and temperature (corrected and uncorrected for dynamical effects) during the descent phase;

- SSP speed of sound, altitude acoustic sounder and impact time measurements;

- GCMS mole fraction measurements of the major compounds (i.e., N_2, CH_4, Ar) during the descent phase;

- DWE zonal wind measurements during the descent phase;

- DISR Solar Zenith Angle (SZA) and altitude and descent speed (derived from optical images) during the descent phase;

- Probe housekeeping data comprising engineering accelerometer, and Radar Altimeter Unit (RAU) measurements;

All sensor models were provided[1] with and without simulated prograde zonal winds and both as noise and no-noise version datasets. The four dataset versions together with a file containing the simulated trajectory (which was used for the generation of the sensor models) allow an optimized analysis of the DTWG reconstruction tool performance.

Fig. 2 and 3 show examples of the modelled sensor output from the HSDS.

[1] All versions of the HSDS are available online at ftp://ftp.rssd.esa.int/pub/HUYGENS/DTWG_Simulated_Data_Set/.

3. THE DTWG TRAJECTORY RECONSTRUCTION TOOL

The DTWG Trajectory Reconstruction Tool (see also Kazeminejad and Atkinson, 2004) was developed at the Space Research Institute of the Austrian Academy of Sciences in Graz, Austria under contract with the Research and Scientific Support Department of ESA. The purpose of the tool is the reconstruction of the Huygens probe entry and descent trajectory as well as the probe attitude during the entry phase (i.e., the angle-of-attack history). The tool uses the NAIF Spice toolkit and was developed in a "multi-planet" mode, i.e., it can be easily adapted for any other probe mission on any other solar system planet. In the current version (Ver.1.0) the tool is also able to reconstruct the Mars Pathfinder entry and descent trajectory and corresponding results are shown in Kazeminejad and Atkinson (2004).

The complete DTWG tool reconstruction procedure consists of the following phases:

1. **Entry Phase**: this phase comprises the reconstruction of the probe altitude and descent speed profile during the entry phase (i.e., from the interface altitude[2] down to the initiation of the parachute sequence at $\sim$ 160 km), the reconstruction of the probe attitude (i.e., the angle-of-attack history), and the reconstruction of the upper atmosphere physical properties (i.e., density, pressure, and temperature) from the measured probe (science and/or engineering) accelerometer data;

2. **Descent Phase**: this phase comprises the reconstruction of the probe altitude and descent speed (from measured atmospheric temperature, pressure, speed of sound, atmospheric composition), the probe longitude drift (from zonal wind measurements of the Doppler Wind Experiment, and the measured Solar Zenith Angle of the DISR instrument), and the derived surface elevation (topography) with respect to the reference surface (from RAU altitude measurements) in the final portion of the descent ($\sim$30 km down to surface impact). The longitude drift reconstruction from the measured SZA is described in Allison *et al.* (2004).

3. **Trajectory Fitting Phase**: this phase allows an adjustment of the initial state vector at the interface altitude in order to achieve an optimum "match" of entry and descent phase by adjusting the probe initial conditions at interface altitude using a classical weighted linear least-squares fitting algorithm.

[2]The interface altitude is defined as 1270 km above Titan's reference surface and represents the official NASA/ESA handoff point where the probe initial state vector and its uncertainties (the covariance matrix) will be provided by the Cassini Navigation team to ESA.

x [km]	-1.312458638E+02
y [km]	-3.824933072E+03
z [km]	-3.697321588E+02
vx[km/s]	-2.346112519E+00
vy [km/s]	5.539336275E+00
vz [km/s]	4.588600223E-01
Titan GM [km^3/s^2]	8.978200000E+03
Saturn GM [km^3/s^2]	3.794062976E+07
Sun GM [km^3/s^2]	132712440041.940

Table 1. Huygens probe state vector at interface epoch UTC JAN 14, 2005 08:58:55.816 (inertial Titan centered EME2000 coordinate system) and primary and perturbing body gravitational constants;

4. SYNTHETIC DATASET RECONSTRUCTION RESULTS

The reconstruction results presented in this paper are based on the HSDS (V1.4) with prograde wind and no noise.

4.1. The Entry Phase

The entry phase is reconstructed by a numerically integrating the equations of motion which are outlined in detail in Kazeminejad and Atkinson (2004). The combination of the following data was used for the entry phase reconstruction effort:

- The initial conditions and physical constants taken from the *Huygens Event File* in the form of a NAIF Spice text kernel with the main parameters as specified in Table 1.

- The axial and normal accelerations derived from the HASI X-Servo, the Y-Piezo, and the Z-Piezo simulated accelerometer measurements;

- The simulated gravitational field with Titan as the primary body and Saturn and the Sun as two perturbing bodies. No flattening of the primary body was taken into account for this simulation[3].

Fig. 4 (upper and medium panels) show the reconstructed altitude and inertial velocity profiles and their respective residuals for the entry phase. One can see that the DTWG tool was able to reconstruct the descent trajectory very accurately. The lower panels of Fig. 4 show the reconstructed upper atmosphere density and temperature profiles in comparison to the Yelle *et al.* (1997) minimum, recommended and maximum profiles. One can readily see that an atmosphere model close to the recommended one was used for the generation of the HSDS.

[3]Note that the DTWG reconstruction tool can simulate an axisymmetric gravitational flattening field for the first zonal harmonic coefficient J_2.

4.2. The Descent Phase

The probe descent phase trajectory was reconstructed from the following datasets:

- The pressure and temperature measurements from the HASI instrument in combination with the GCMS measurements of the mole fractions (needed to infer the mean molecular mass of the gas mixture) of the major atmospheric constituents to derive altitude and descent speed;
- Optionally the SSP speed of sound measurement (in the altitude range from ~46 km down to the surface) in connection with the HASI pressure measurements to derive altitude and descent speed;
- The DWE zonal wind measurements and the DISR Solar Zenith Angle to derive the probe longitude drift;
- The HASI and SSP accelerometer measurements at probe surface impact in order to constrain the probe impact time;
- The two RAU altitude measurements to derive the surface elevation in the final part of the descent phase (~30 km down to 1 km);

The descent phase reconstruction was done in "reverse" mode, i.e., starting from the probe impact time (with an assumed distance to the planet center of 2575 km) upwards. This constrains the initial altitude error (which increases during the reconstruction process due to the various measurement errors of the input data) to a maximum of ±10 km (maximum estimated surface elevation with respect to the reference surface).

Fig. 5 shows the results of the descent phase reconstruction. The upper and middle panels show the direct comparison and the corresponding residuals for the altitude and the descent speed reconstructions. The lower left panel shows the reconstructed probe longitude drift from measurements of the DWE experiment (i.e., zonal wind speed measurements) and the lower right panel depicts the reconstructed surface elevation from the comparison of RAU-1 measurements with the reconstructed altitude profile from atmospheric measurements. One can see that the DTWG tool accurately reconstructed the descent trajectory.

5. ENTRY/DESCENT PHASE MERGING STRATEGY

As the entry phase and the descent phase will be reconstructed from completely different data sources (i.e., the initial state vector with corresponding uncertainties and the measured accelerations for the entry phase, and the various atmospheric properties and radar measurements for the descent phase) the following three scenarios could be envisaged:

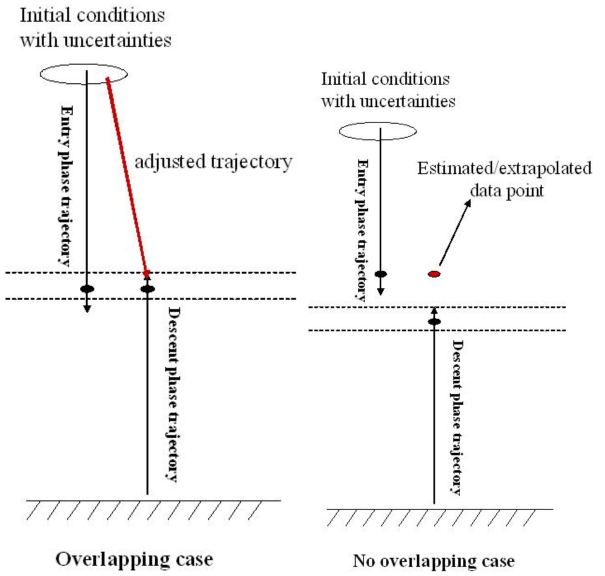

Figure 6. Entry/Descent Phase Merging scenarios; Left: overlapping case; Right: Non overlapping case;

1. The *optimum case* where the reconstructed entry and descent trajectory overlap each other and perfectly fit together. Due to the limited accuracy of the initial state vector and the noise and measurement errors of the various instruments, this case is very unlikely;

2. The *overlapping case* where the two trajectories overlap each other. In other words, for a certain time period altitude and descent speed values are available from both the entry and the descent phase trajectory reconstruction effort (see left panel of Fig. 6);

3. The *non overlapping case* where the two trajectories do not overlap each other. This scenario could happen if the actual state vector is too far away from the estimated one and the integration of the equations of motion would stop too early due to the large systematic errors (see right panel of Fig. 6).

The first case would not need any trajectory merging efforts. However, the second and third one would need to be merged in order to provide one consistent entry and descent trajectory. This merging capability is implemented into the DTWG tool in the form of a weighted linear least squares fitting algorithm, where the calculated measurement values are the altitude and/or descent speed from the entry phase and the "fitting observations" are the corresponding reconstructed values from the descent phase. The adjusting parameters are the six values of the initial state vector in numerical integration process of the equations of motion during the entry phase (the first iteration would be the state vector as delivered by the Cassini Navigation team). The testing of the trajectory merging tool capability is currently ongoing work.

6. INSTRUMENT FAILURE SCENARIOS

Any planetary probe trajectory reconstruction effort bases on a variety of instrument datasets and one needs therefore to investigate various instrument failure scenarios and their impact on the quality of the reconstruction. Part of this exercise is the definition of *critical*, *significant* and *minor* instrument datasets for both the entry and the descent phase. The difference between a critical and a significant dataset is that the lack of a critical dataset would make a trajectory reconstruction process impossible whereas the lack of a significant one would only impact the quality and reliability of the reconstruction result. A minor dataset increases the quality of the reconstruction effort but a still fairly consistent trajectory could be achieved without this input. It should be noted however that even a minor dataset could become significant or even critical if a series of input data would be missing due to a major failure of the probe system.

The entry phase reconstruction is based entirely on the measurement of the probe accelerometer data. Those are provided by the HASI instrument and to some extent (i.e., lower sampling rate and acceleration detection limits) by the probe engineering housekeeping data. The HASI accelerometer measurements are therefore considered a significant dataset for the entry phase.

The descent phase reconstruction is based on the measurement of the altitude dependent atmospheric properties like pressure and temperature. The HASI pressure and temperature measurements therefore represent a critical dataset. Note that alternative measurements which could replace one or both of these significant measurements are only available in certain parts of the descent phase (e.g., SSP speed of sound measurements from $\sim$46 km to the surface, RAU altitude measurements from $\sim$30 km down to the surface, etc.). The SSP impact sensor measurement will provide an important input for the initial epoch of the descent phase reconstruction (done in reverse mode, from the surface upwards), but could in case of failure be replaced by the measurements from the HASI accelerometers and is therefore only significant in case of a HASI accelerometer failure during the entry phase. The RAU altitude and SSP acoustic sounder datasets can be considered as minor but might however be the only reliable dataset (and therefore critical) in case of a complete HASI failure.

7. CONCLUSIONS

The Huygens Descent Trajectory Working Group has developed a dedicated tool for the reconstruction of the Huygens entry and descent trajectory on the basis of the measurements from the 6 scientific instruments and a subset of the probe's engineering housekeeping data. The tool has so far been successfully tested on the Mars Pathfinder Mission data, and a specially designed synthetic dataset that simulates the content and format of all the relevant probe sensors. The reconstruction results for the synthetic dataset are presented and discussed in this paper. The DTWG trajectory reconstruction tool was developed in the framework of a contract between the European Space Agency and the Austrian Academy of Sciences and can therefore be adapted for future planetary probe missions if required by the Agency.

8. ACKNOWLEDGEMENTS

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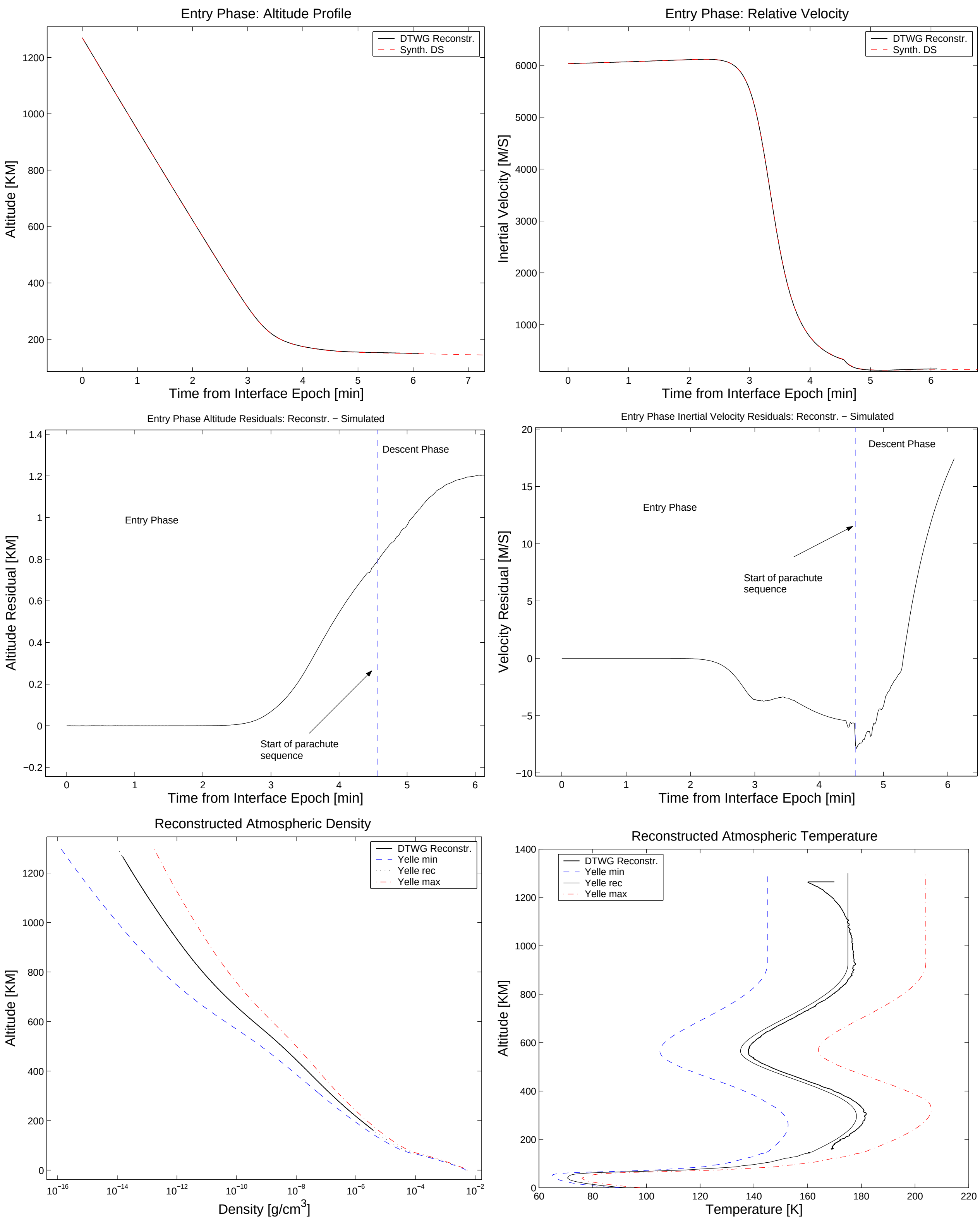

Figure 4. Entry phase trajectory reconstruction: Upper panels: comparison of reconstructed (solid) and simulated (dashed) altitude and inertial velocity profiles; Middle panels: corresponding altitude and velocity residuals (reconstructed - simulated); Lower panels: reconstructed atmospheric density and temperature profiles compared to the Yelle et al. *(1997) minimum, recommended, and maximum profiles; one can see that an atmosphere model very similar to the recommended Yelle model was used for the generation of the synthetic dataset. The interface epoch is UTC JAN 14, 2005 08:58:55.816.*

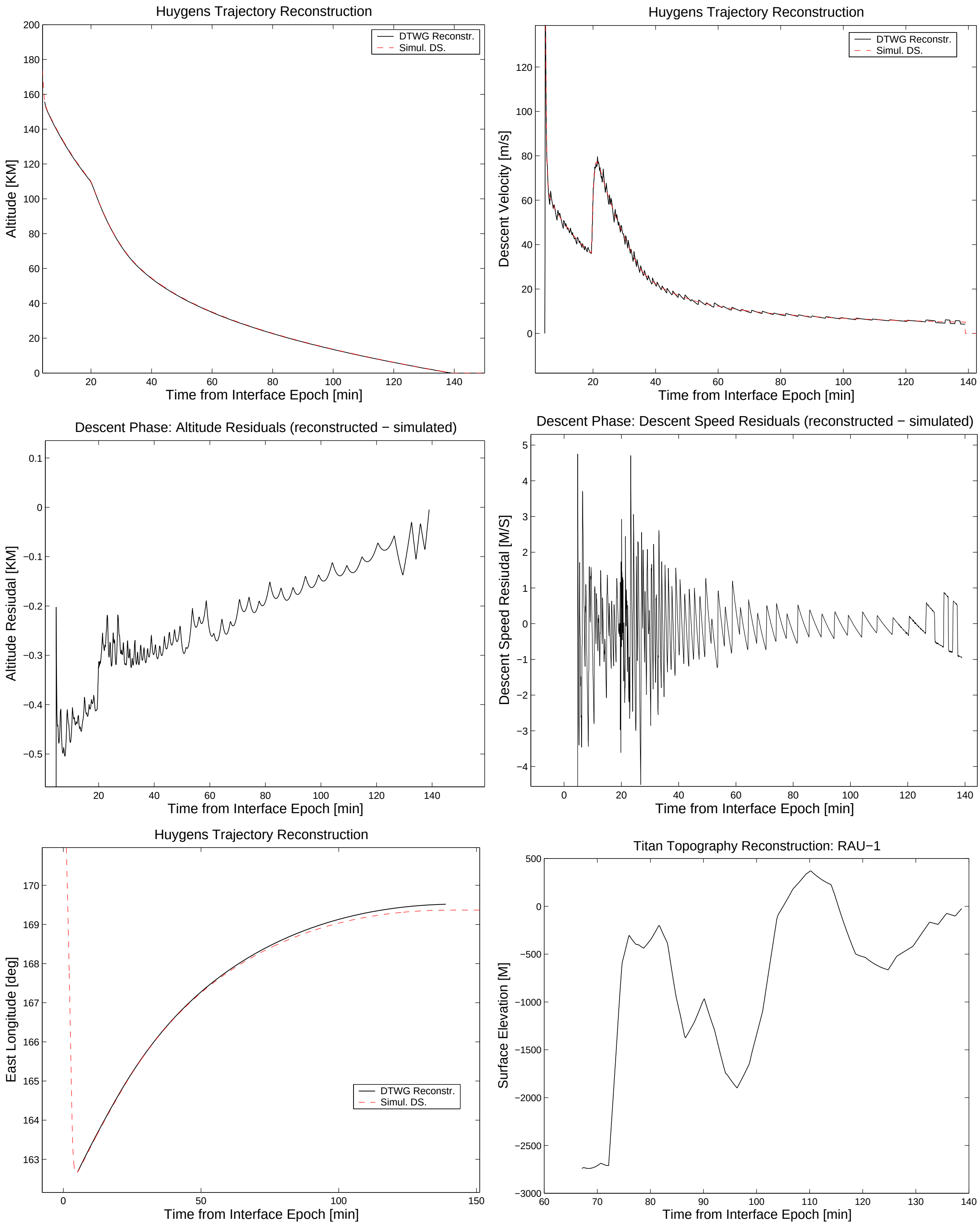

Figure 5. Descent phase trajectory reconstruction: Upper panels: comparison of reconstructed (solid) and simulated (dashed) altitude and descent speed profiles; Middle panels: corresponding altitude and descent speed residuals (reconstructed - simulated); Lower panels: reconstructed probe longitude drift due to zonal winds (left) and surface elevation from RAU-1 data (right). The interface epoch is UTC JAN 14, 2005 08:58:55.816.